Photonic Integrated Circuit TUned for Reconnaissance and Exploration (PICTURE)

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Introduction & Science Objectives

PICTURE Instrument Concept

Subsystems

- Arrayed Waveguide Grating
- Quantum Cascade Laser
- Photonic Lantern

Systems Throughput

Conclusions

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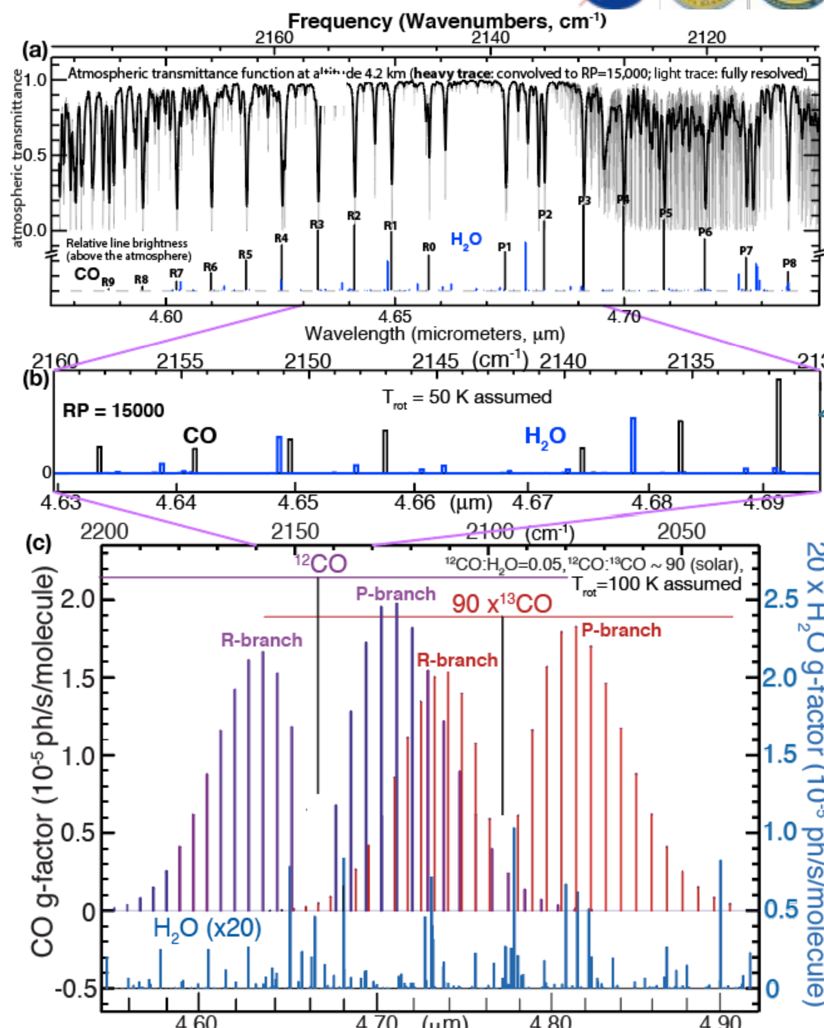
Comet Science

Use of a PICTURE-type instrument in space would enable line-by-line comet studies free of atmospheric attenuation.



Representative atmospheric transmittance above Mauna Kea, at the spectral RP of PICTURE (15000), with the fully resolved (RP ≅ 10^6) transmittance overplotted (light trace).

Convolved spectra (RP = 15000), demonstrating the need for the higher RP of PICTURE to separate emission lines. Modeled stick spectra showing relative fluorescent intensities (at the top of the atmosphere) and positions for CO (in black, with ro-vibrational designation)

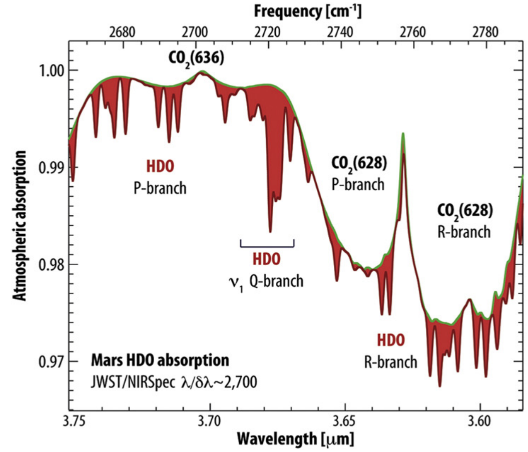
Stick spectra for modeled fluorescent emission lines of ^{12}CO, ^{13}CO, and H_2O, assuming a rotational temperature of 100 K expected for a bright and highly productive comet, for the example of H_2O production rate $>10^{29}$ molecules/s together with a favorable observing geometry.

NIR Study of Planetary Atmospheres

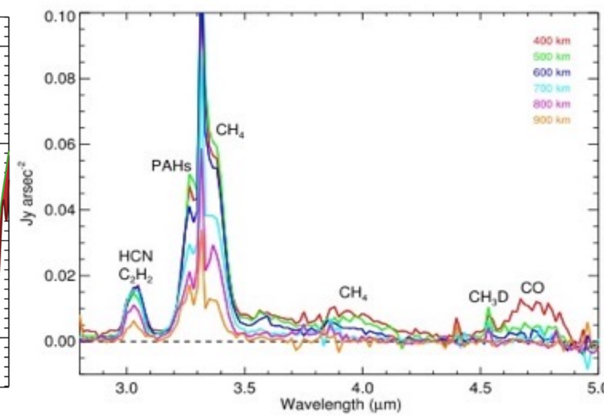
Mars: MIR spectral prediction for Mars at RP~2700 that will be achieved by JWST NIRSpec. The resolution achievable by PICTURE (RP~15000) will greatly improve the separation of gas emission bands, including isotopologues.

Titan: Cassini VIMS daytime spectra (RP~300) of Titan's limb (400-900 km) showing gas emissions. The PAH band at 3.3 µm is unresolved; likewise, C_2H_2 and HCN at 3.05 µm.

Mars

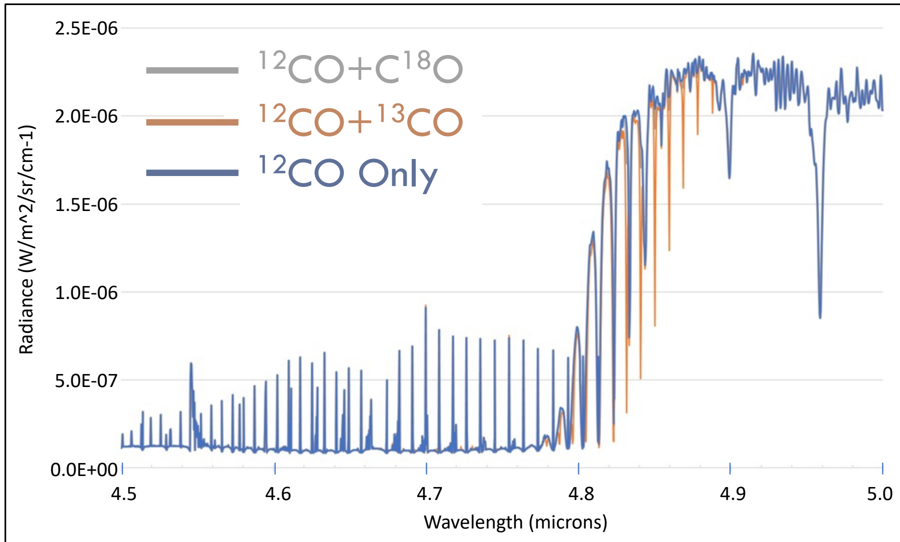


Titan



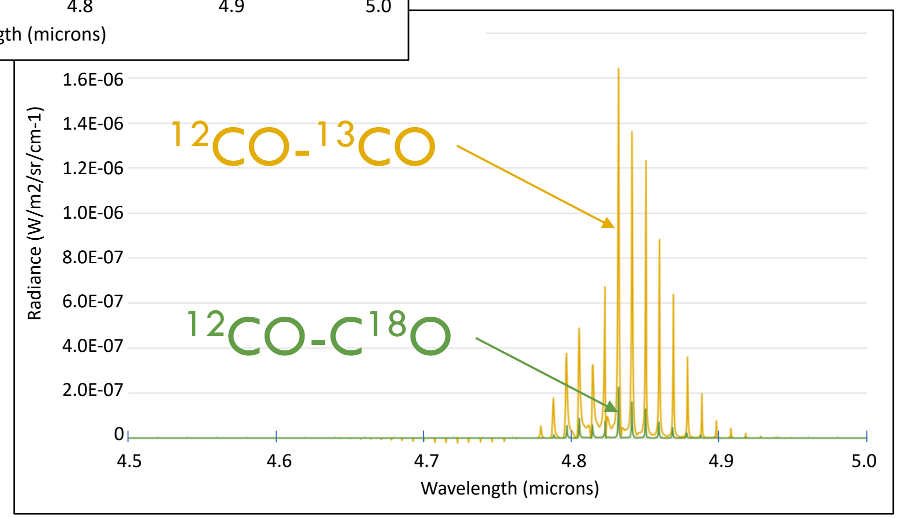
Planetary Science - Titan

- Accurate measurement of the $^{12}C/^{13}C$, $^{16}O/^{18}O$ and other isotopic ratios in CO and other gas species can provide strong constraints on building blocks of planets and their satellites, and also on subsequent photochemical evolution of the atmosphere
- PICTURE's high RP will allow over-lapping isotopologues bands to be separated and permit more accurate measurements.



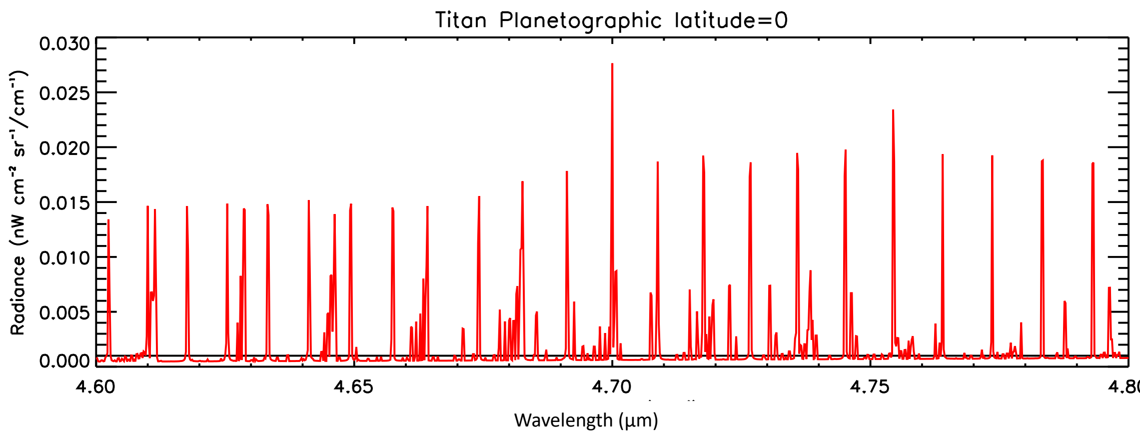
Titan spectrum from 4.5 µm to 5.0 µm at the PICTURE's RP~15000.

- Emission differences due to the presence of isotopologue species ^{13}CO and $C^{18}O$.
- PICTURE will be able to measure the abundance not just of CO, but isotopologues as well, allowing insights into planetary building blocks.

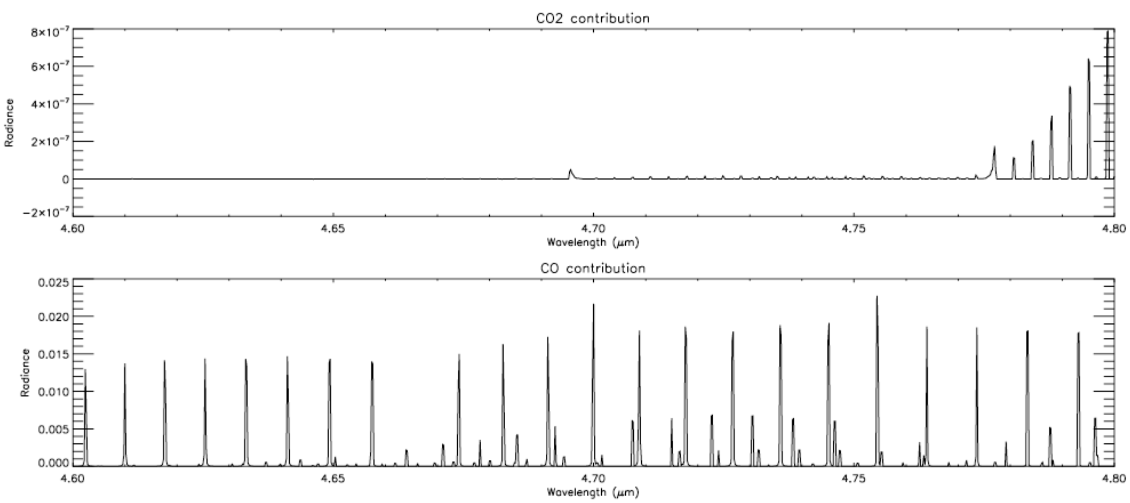


Planetary Science - Titan

Simulation of the spectral response of Titan at low altitude for an instrument with RP ~15,000 (or equivalently FWHM ~ 0.31 nm)



Spectral simulation for Titan at low latitude centered around 4.7 μm.



Effects (contributions) of CO_2 and CO gases at 4.7 μm.

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PICTURE Objectives & Development of Critical Technologies

- Our goal for this PICASSO is to build one of the N identical coherent heterodyne PICS slices for measurements of CO at ~4.65 µm
- Targeting resolving power of ~15,000 or better

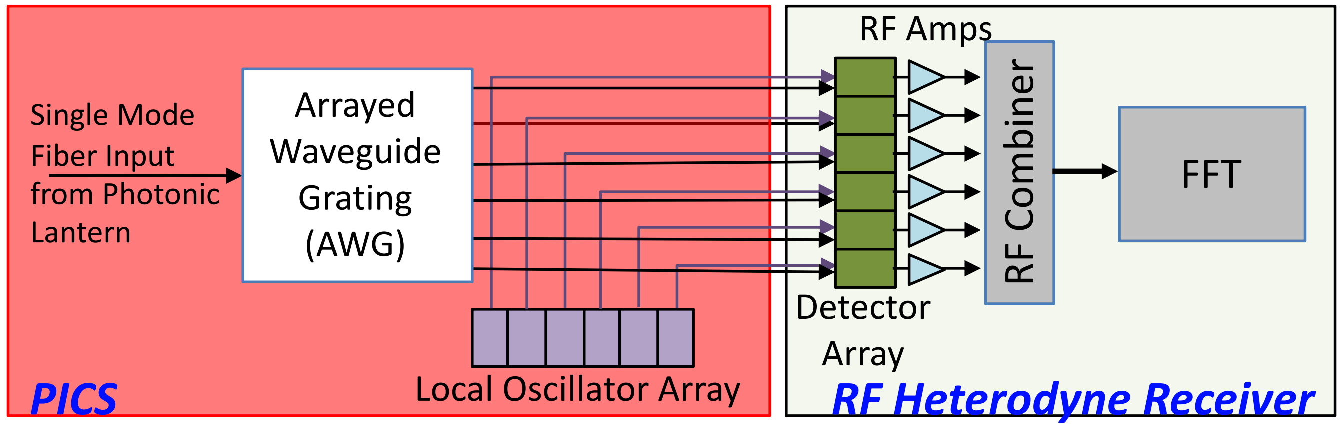
Photonic Integrated Circuit TUned for Reconnaissance and Exploration (PICTURE)

Collection Optic – Telescope → Fiber delivery system – Photonic Lantern → Photonic Integrated Circuit Spectrometer (PICS) → Electronics, Data Processing, Storage and/or Networking

- PICASSO
  - MIR AWG ~4.7 µm
  - MIR QCL at ~4.7 µm as LO
- SBIR/STTR
  - Photonic Lantern – early stage, developed toolsets necessary for MIR PL demonstration in the future.

PICTURE Instrument Concept

Our goal for this PICASSO is to build one of the N identical coherent heterodyne PICS slices for measurements of CO at ~4.65 μm



- Light from the telescope couples into the PICS via a PL with MMF input and N SMF outputs.
- In this case, each PICS will have a dedicated tunable LO array.
- Photomixing of the received input signal and individual elements in the LO array at each pixel of the detector array will provide improved sensitivity and spectral responses.
- A radio frequency (rf) heterodyne receiver (on the right) backend is comprised of rf amplifiers and rf combiners for each of the identical PICS slices.
- The rf output signals from all the PICS slices are then combined via a 2nd rf combiner before sending the signal for data processing.

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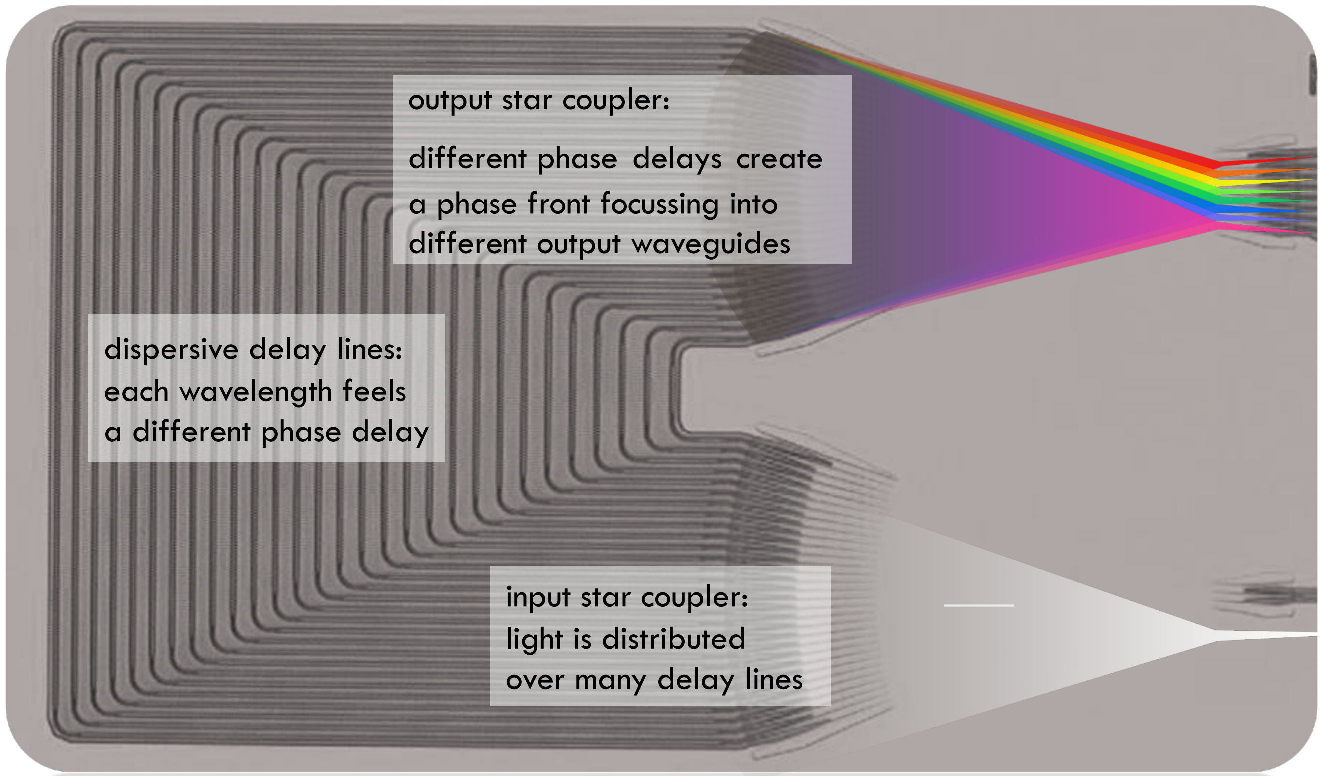
Arrayed Waveguide Grating (AWG) Spectrometers



AWG Figure of Merit (FOM)

Crosstalk (XT)

- Indicates how much light goes in other channels

$$CXT_x = \frac{\int_{3\text{dB},x} t_{a,x}\,\mathrm{d}\lambda}{\int_{3\text{dB},x}\left(\sum_{y=1}^{N_{ch}} t_{a,y} - t_{a,x}\right)\mathrm{d}\lambda},$$

where, t_a is the transmission of the channel, x is the channel number and N_{ch} is the total number of channels

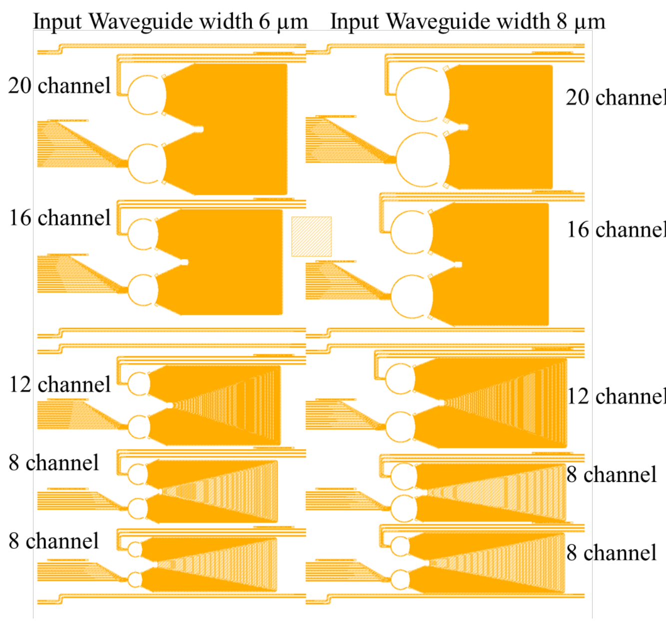
$$\overline{XT} = \frac{1}{N_{ch}-1}\sum_{x=1}^{N_{ch}} CXT_x$$

- Phase noise from side walls due to side wall roughness
  - Included in the model amplitude error for propagating field in waveguides
  - Can be minimized by using wide waveguides
- Coupling into higher order modes
  - Not included in the model
  - Increases with waveguide width

Insertion Loss

- Light lost at star coupler interfaces.

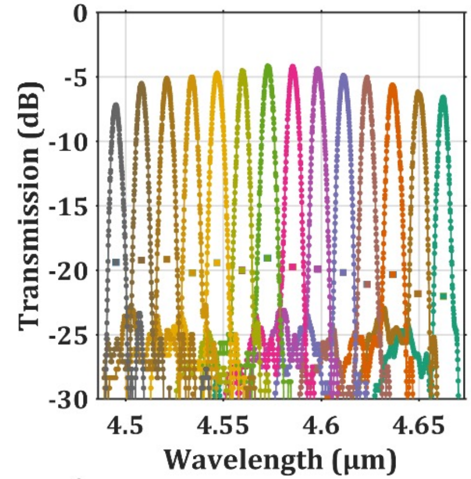
Arrayed Waveguide Gratings (AWG)



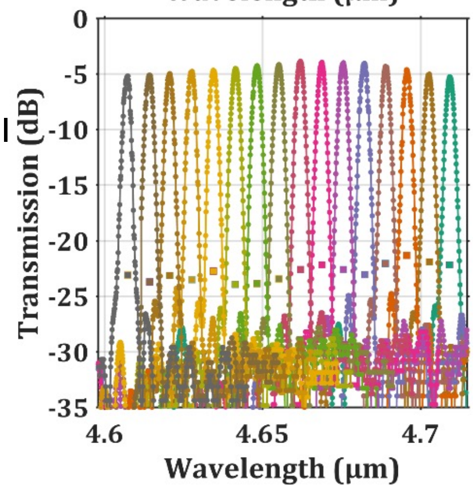
Mask plate showing various AWGs with different numbers of channels and input waveguide widths.

Measured Transmission of Fabricated AWGs

14 channel AWG with 170 GHz channel spacing.



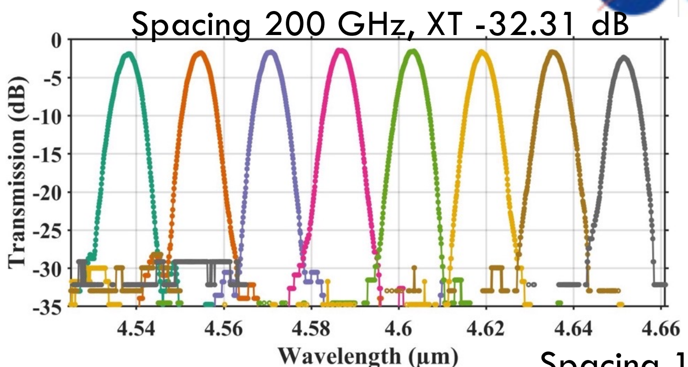
16 channel AWG with 87 GHz channel spacing.

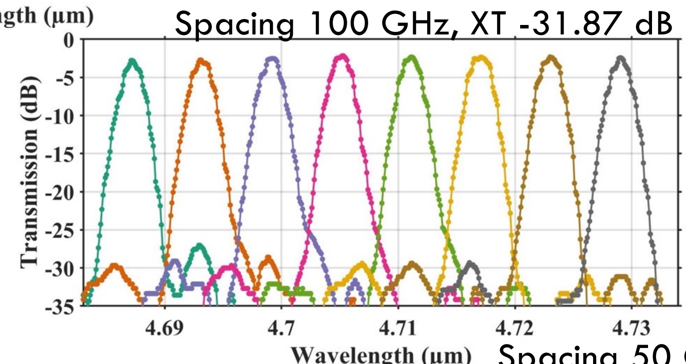


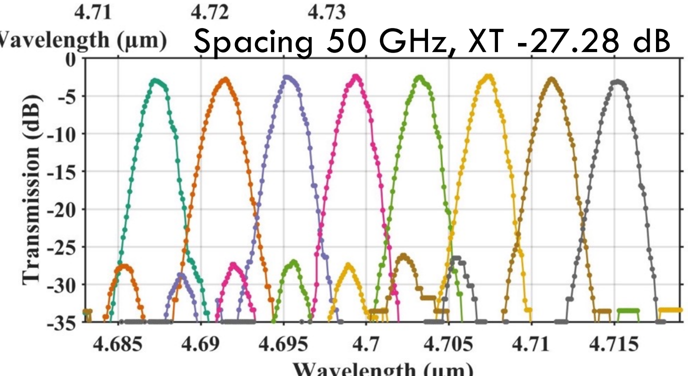
Silicon-on-Insulator (SOI) AWGs for PICTURE

- SOI AWGs @ 4.7 µm wavelength range have been demonstrated with 1500 nm thick silicon and 2 µm thick buried oxide layers.
- Measured transmission and crosstalk (XT) of eight channel AWGs with 200 GHz, 100 GHz and 50 GH resolution.
- Phase noise minimization ensures low crosstalk even at higher resolution

A. Malik, et al., Optics Letts., 2020







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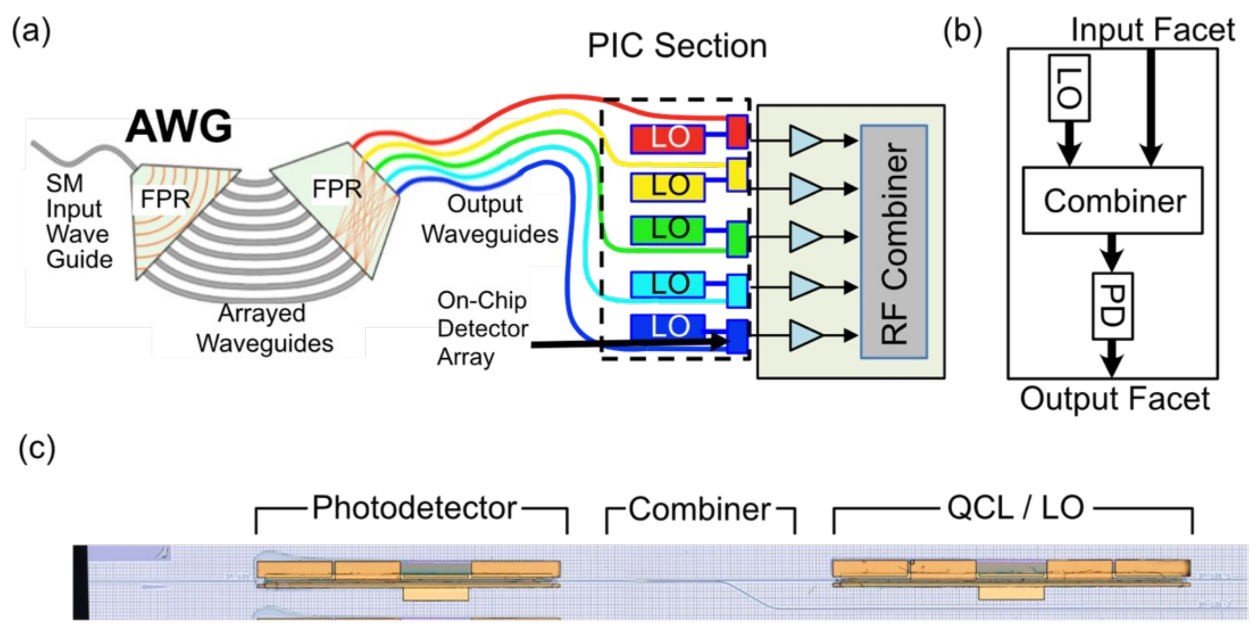
Photonic Integrated Circuit (PIC) for PICTURE



(a) Schematic of the PIC portion of the PICTURE instrument.

(b) Schematic of the PIC fabricated recently by our team.

(c) Optical microscope image of the fabricated PIC where a QCL is integrated with a 2×1 combiner and an on-chip photodetector.

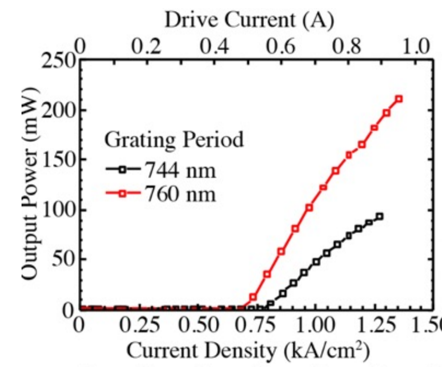
Quantum Cascade Lasers (QCLs) on Silicon (Si)

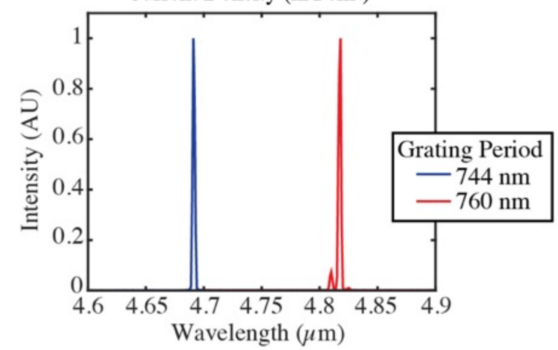
$\lambda = 4.8$ µm Fabry-Perot and Distributed Feedback lasers

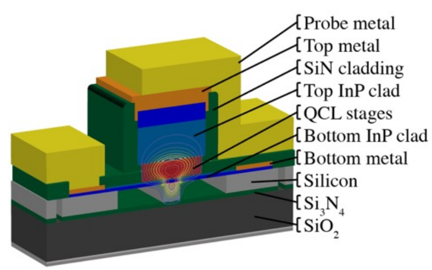
Threshold current densities < 1 kA/cm^2

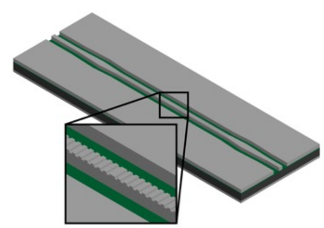
Over 200 mW output (hybrid facet); 30 mW in Si waveguide

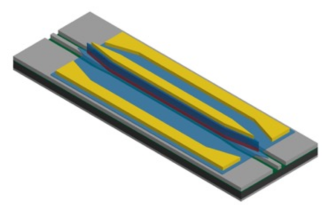
Up to 100 °C pulsed operation

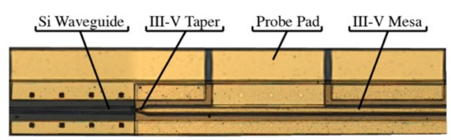


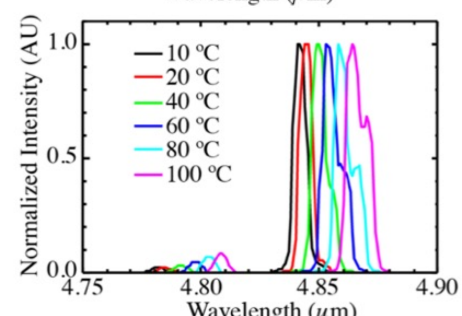






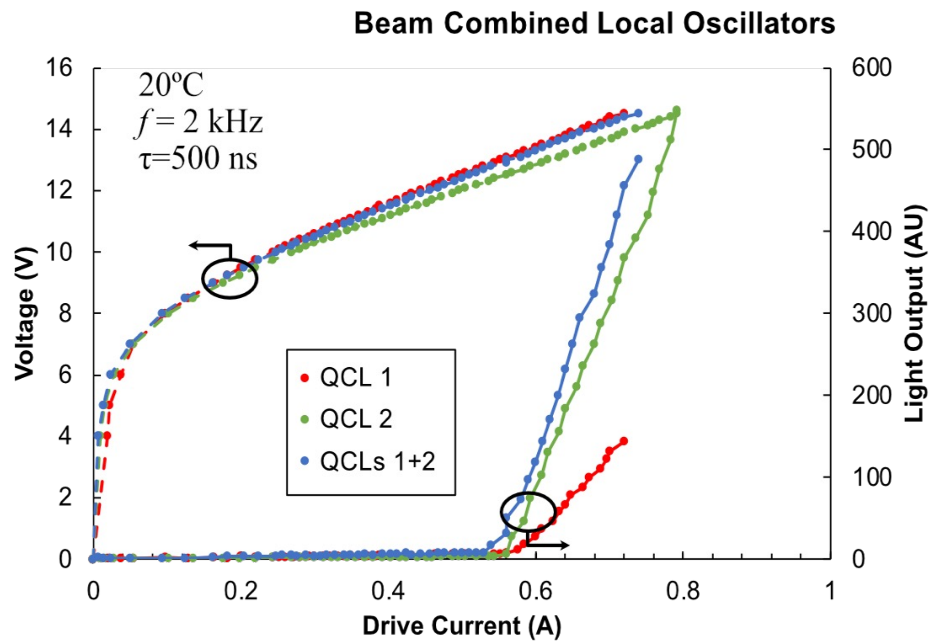






A. Spott, et al. Optica **3**, *545 (2016).*
A. Spott, et al. Photonics **3**, *35 (2016).*

Quantum Cascade Laser (QCL) – Local Oscillator

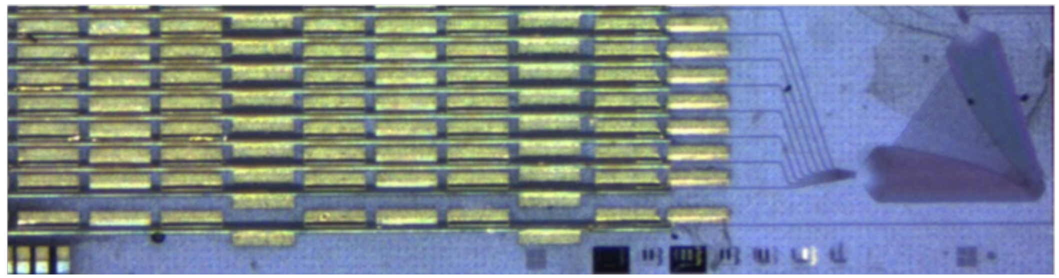


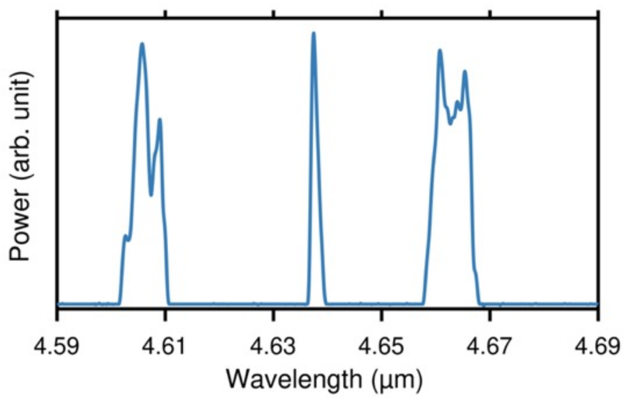
Light emission and voltage vs. drive current per laser for two QCLs integrated with a 2×1 channel combiner and light emitted from a single silicon facet. When the QCLs were operated together (red line), a single current source was used to drive both lasers at once.

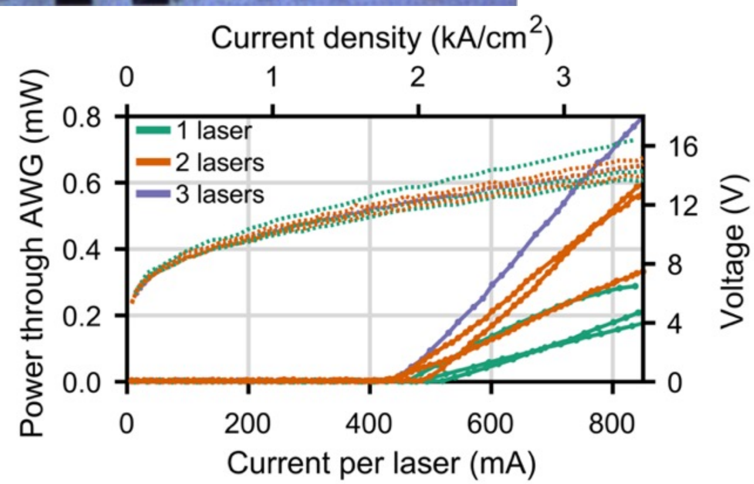
Multi-spectral QCLs

QCLs combined with an AWG

- 3 QCLs wavelength beam-combined
- Fully-integrated: QCLs and AWGs on the same chip

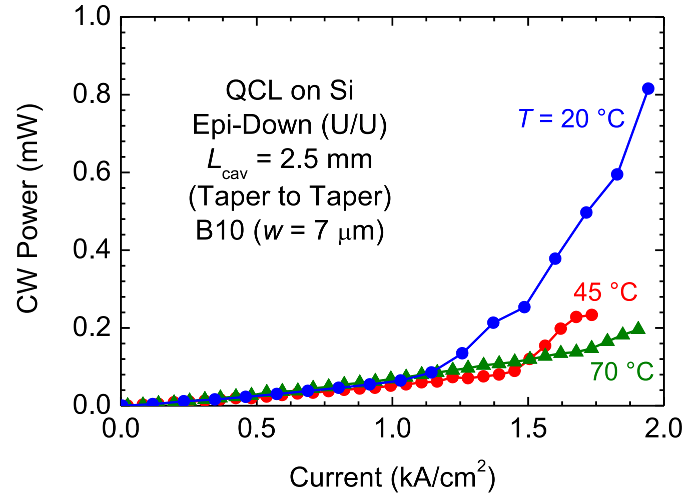


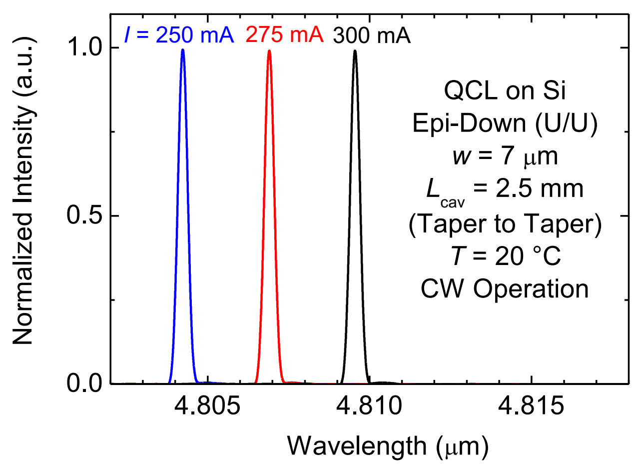


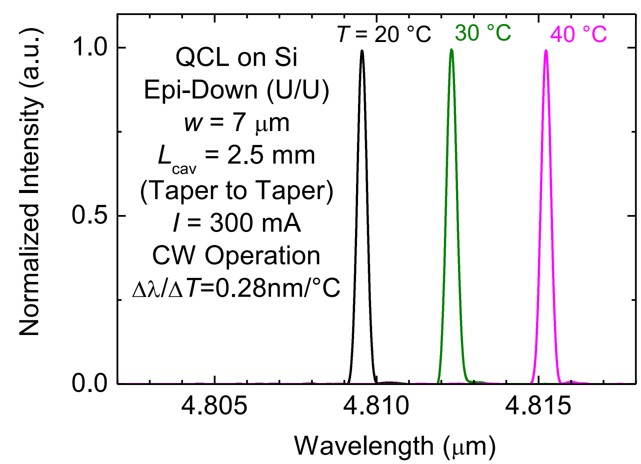


E. J. Stanton, et al., Photonics (2019).

Room Temperature CW QCL Tests @ NRL







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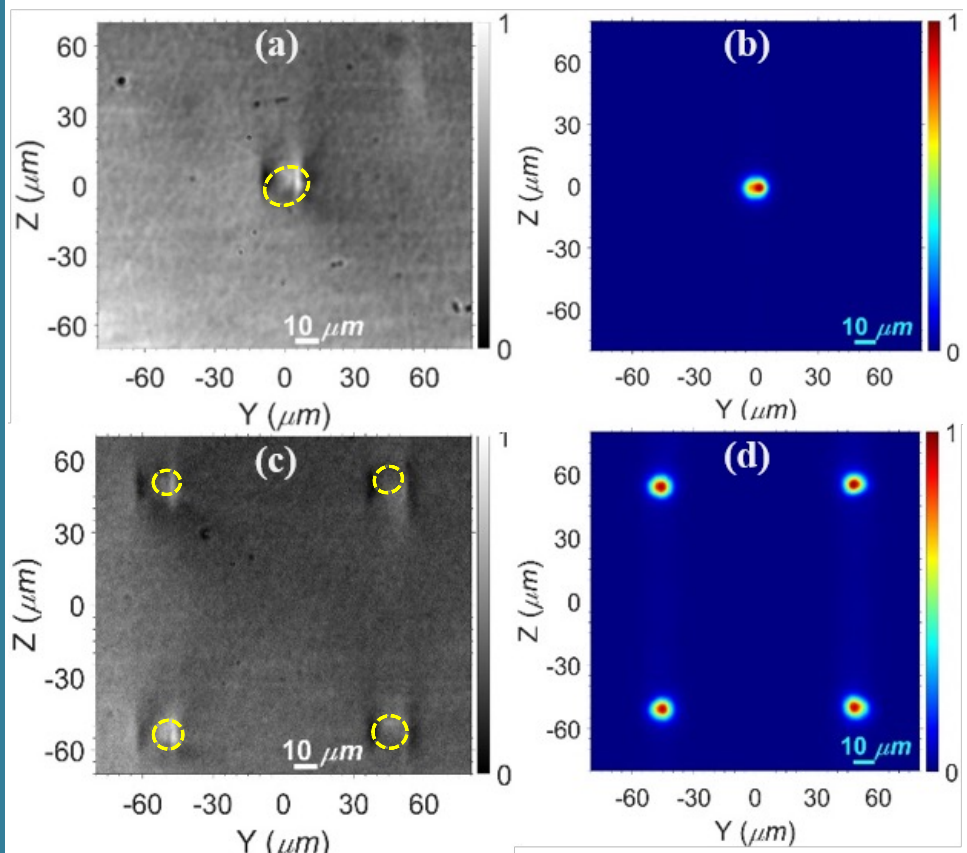
Photonic Lantern (PL) Toolsets



Rear-end cross-section of the input waveguide (a) and its mode profile (b) at 1064 nm, respectively.

Rear-end cross-section of a 1×4 beam splitter with 100 μm lateral separation between the arms (c) and its mode profile (d) at 1064 nm.

The yellow dashed lines in (a) and (c) indicate the approximate location of the beam profile at $1/e^2$ of the maximum amplitude.

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Estimated Instrument System Throughput

Instrument system throughput (based on 10 Identical PICs).

	Space instrument
Telescope to SMF	78%
SMF to 10 identical PICs (w/3 dB grating coupler loss)	5%
PIC	50%
2 X RF Signal Combiner (in RF Heterodyne Processor)	10 (combining) * 83% (insertion loss) ^{2}
TOTAL	~13%

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Conclusions and Future Plans

- Developed science objectives
- Demonstrated Mid-IR Ge-on-Si AWGs with performance similar to their telecom counterparts
- Demonstrated CW, room temperature operation of Mid-IR QCL on Si.
- Continue to develop critical technologies needed to demonstrate PICTURE instrument
  - Mid-IR Photonic Lantern
  - AWG
  - QCL
  - Detectors
  - Photonic Integrated Circuit
- Systems Demonstration

backup

PICASSO/PICTURE Science Objectives

What science question(s) will ultimately be addressed?

Science Question		Science Objective	Measurement	Instrument Requirement
1. What do comets tell us about the origins of planets and moons, and the delivery of volatiles from the outer to the inner solar system?	**1.1**	Determine the relative proportions of abundant gases (CO and CO_2) to H_2O in JFC and OCC, and the variability that may be indicative of processing.	Measure the bulk abundances of CO, CO_2 and H_2O via their near-infrared spectral bands.	MIR spectroscopy covering the key bands of H_2O (2.7 µm), CO_2 (4.2 um) and CO (4.8 µm) at R~500-2000
	1.2	Determine the spatial and temporal variability of gases in the coma during comet approach and perihelia, for comets of differening periods.	Measure the spatial and temporal abundances of CO, CO_2 and H_2O via their near-infrared spectral bands.	MIR spectroscopy covering the key bands of H_2O (2.7 µm), CO_2 (4.2 µm) and CO (4.8 µm) at R~500-2000
	1.3	Determine the relative abundances of simple organic molecules such as CH_4, C_2H_6, CH_3OH, H_2CO in multiple comets.	Measure the abundances of trace gases (CH_4, C_2H_6, CH_3OH, H_2CO etc.) via their near-infrared spectral bands.	MIR spectroscopy covering organic molecular bands at 2-5 µm, with R~2000-5000.
	1.4	Quantify isotopic ratios in comet volatiles including D/H, $^{13}C/^{12}C$, $^{15}N/^{14}N$ and $^{18}O/^{16}O$ to learn about comet origins and compare to other objects.	Measure the abundances of strong and weak isotopologues, e.g. H_2O and HDO, $^{12}CH_4$ and $^{13}CH_4$, to compute isotopic ratios.	MIR spectroscopy covering organic molecular bands at 2-5 µm, with R~10000-20000.
2. What can we learn about the origin and evolution of planetary atmospheres from their trace gas and isotopic composition?	**2.1**	What chemistry is occurring in reducing and oxidizing planetary environments?	Measurement of trace gas composition.	MIR spectroscopy to determine gas abundance through absorption and emission bands.
	2.2	What is the net energy balance of planets?	Measurement of total absorbed solar radiation.	MIR spectroscopy to determine gas abundance through absorption and emission bands.
	2.3	What is the origin of planetary atmospheres, including primary and secondary contributions?	Measure abundance of gas isotopologues to determine isotopic ratios.	MIR spectroscopy to determine gas abundance through absorption and emission bands.